Extreme Loads due to Wave Breaking Against Platform Column

Abdillah Suyuthi
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway.

Sverre K. Haver
StatoilHydro
Stavanger, Norway.

ABSTRACT

The purpose of the paper is to compare impact loads due to breaking waves obtained using an available recommended practice with results obtained from model tests. Our focus is not to compare prediction and experiment on an event by event basis. Rather focus is given to the comparison of q-probability wave impact loads against platform columns. The q-probability value notation means the value corresponding to an annual exceedance probability of q. Model tests including measurements of impact loads on platform columns carried out some few years ago are available for this study. One of the tests was with a semi-submersible platform, while the other tested was a tension leg platform. In connection with introducing the model test setup, it will also be shown how effects of sensor dynamics can be eliminated. Following the environmental contour line method, the q-probability impact events are obtained by estimating the 90% and 95% value of the 3-hour extreme value distribution for the worst sea state along the q-probability contour. Uncertainties related to the estimation of the 90% and 95% value will be discussed. They are partly quantified using parametric bootstrapping, i.e. simulating many equally possible samples of model test size from an assumed true model. Finally, q-probability values estimated using an available recommended practice are obtained and compared with model test results. It is demonstrated that large uncertainties are associated with the model tests, due to a limited number of tests for the governing sea states. In spite of this, the conclusion is that the recommended practice is in reasonable agreement with model tests results for q = 10^{-2}, whereas model test results suggest larger impact loads than the recommended approach for q = 10^{-4}.

KEY WORDS: Breaking-wave; slamming; stochastic; contour line; platform column.

INTRODUCTION

Breaking waves may cause large and rather localized impact forces on offshore structure compare to non-breaking waves (Ochi and Tsai, 1984). Ochi and Tsai (1984) carried out an experiment by generating breaking waves in a 40-meter long wave tank. During the tests, impact pressure was measured at the front face of a circular cylinder representing a column of an offshore structure. They propose a method to statistically predict the magnitude of impact pressure (including extreme values) produced by deep water waves breaking against a circular cylinder.

Zhou et al. (1991) conducted laboratory measurements of the pressure distributions on surface-piercing vertical cylinders due to breaking waves. Despite repeatability of the controllable experimental conditions, they found that the highest impact pressures are subject to considerable variability, including pressure oscillations, from run to run. This high impact region is found to be localized in space and time, and the variability is attributed to the random dynamics of the breaking wave front and the entrapped air. They concluded that the largest pressures is essentially an inherent random phenomenon – even with identical wave conditions.

For design purpose, the magnitude of the breaking wave loads may be very important. The experienced load will vary depending on the breaking process at impact. In their experiment, Wienke and Oumeraci (2005) set up five conditions of wave breaking by adjusting the distance between breaking point and cylinder. This arrangement produced five different developments of breaking wave impact, which could represent breaking events in reality. As a note, the exact breaking location cannot be identified by wave gauges or other measuring instruments with a sufficient accuracy. They suggested visual evaluation (video records) as the most reliable determination tool for breaking detection.

In this study, we do not investigate the various impact events into detail, i.e. we do not know what is the actual breaking development at impact. The background for this is that we aim for the distribution function of the 3-hour maximum impact load for the governing q-probability sea state. Our hypothesis is that if a sufficient number of realizations of the 3-hour maximum impact loads are available, the distribution function thus obtained should represent a reasonable approximation to the underlying true distribution. That distribution will define a population representing a variety of breaking development.

The model tests for two platforms were carried out a number of years ago. A semi-submersible platform was tested by Marintek and a tension leg platform was tested by Marin. At that time no detail consideration of necessary sample size for obtaining proper estimates of q-probability impact loads was made. Here the number of observations is given by
what was done during the tests. But in order to remind the reader on the
importance of sample variability when sample sizes are small, uncertainties associated with the estimation of q-probability forces
from samples of limited size will be discussed.

An important part of estimating q-probability values of complex
response problems is to have a procedure for doing so without having
to perform a full long term analysis. Here we will use the
environmental contour method.

ENVIRONMENTAL CONTOUR LINE METHOD

The environmental contour line method is described into detail in
Winterstein et al. (1993), Kleiven and Haver (2004), Haver and Kleiven
(2004), and Haver and Winterstein (2008). Here we will briefly present
the steps of the method. For more details, the reader is referred to e.g.
the references above.

The environmental contour line method consists of the following steps:

1. The first step is to establish the contour lines, i.e. pair of \( H_s \) and \( T_p \)
corresponding to the same annual exceedance probability. This is
rather straightforward as the joint probability density function for
\( H_s \) and \( T_p \), \( f_{H_s,T_p}(h,t) \), is available. Examples of contour lines are
shown in Fig. 1. These contour lines are actually the contour lines
used in the two model tests.

![Contour Lines](image)

Fig. 1 shows the 90% band of occurrences of \( x \)
tested for \( p=0.9 \) and \( 0.95 \). Number of experiments was set to be 2000.

2. Second step is to identify the worst sea state along the contour.
Some few sea states are selected such that they cover the range
within which the worst sea is likely to be located. Some few (3-5)
3-hour tests are done for all of these and based on these the worst
sea state in view of the problem under consideration is selected.

3. As the worst sea state is identified, a reasonably large number of 3-
hour test must be done for this sea state. We will later discuss what
would be a proper number of realizations.

For each of the 3-hour realizations for the worst sea state, the
maximum impact force is identified. Denoting the number of tests
for the worst sea state by \( N \), we will have a sample of size \( N \) for the
3-hour maximum impact force, \( X_{3h} \). A reasonable probabilistic
model for \( X_{3h} \) could be the Gumbel model:

\[
F_{X_{3h}}(x) = \exp \left( - \exp \left( \frac{x - \mu}{\beta} \right) \right)
\]

(1)

As mean, \( \mu \), and standard deviation, \( \sigma \), are known from the sample,
the parameters can be estimated using the moment principle by (see
e.g. Bury, 1975):

\[
\beta = 0.7797 \sigma
\]

(2)

\[
\mu = \overline{x} - 0.57722 \beta
\]

Finally, as the distribution function of \( X_{3h} \) is estimated, the q-
probability value is estimated by the value not exceeded by
probability \( p \). Following the recommendations in Norsok (2007),
\( p=0.9 \) is adequate for \( q=10^{-2} \). It is important to keep in mind that
this method is an approximate method. \( p \) will to a certain extent be
problem dependent. However, \( p=0.9 \) is often a rather good
approximation.

AN ASSESSMENT OF UNCERTAINTIES IN MODEL TEST
PREDICTIONS

When predicting the 90% largest impact load from a sample of limited
size, there are two uncertainties that cannot be avoided. Uncertainties
will be associated with the selected probabilistic model and
uncertainties will be associated with the estimation of the parameters
of the model. Here we will concentrate on the latter. A priori, the
parameter estimates given by Eq.(2) will be random variables, denoted
estimators. The estimators should be consistent. That means they
should be unbiased, i.e. \( E[^\mu] = \mu \) and \( E[^\beta] = \beta \). Furthermore, they should
have a standard deviation approaching 0 as \( N \to \infty \).

Whether or not the estimators are unbiased can be investigated using
e.g. parametric bootstrapping. We assume that the fitted Gumbel model
is the true model. From the fitted distribution we generate M samples of
size \( N \) using Monte Carlo method. By estimating the Gumbel
parameters for each simulated sample of size \( N \) and calculate the
average of the M estimates, the bias can be investigated looking at
\( \overline{\mu} / \mu \) and \( \overline{\beta} / \beta \). Using \( M=2000 \), these ratios are shown versus \( N \) in Fig.
2. It is seen that as the number of observation, \( N \), equals to 20 , the bias
is in the order of 2-3% for parameter \( \beta \) and 1-2% for parameter \( \mu \). For
a sample size 7, the bias in \( \mu \) is 4% and the bias in \( \beta \) is 5-6%. In view
of other uncertainties, we will consider the estimates unbiased for a
sample size of 20 or larger, but one should possibly correct for bias
when sample size is as small as 7.

![Bias](image)

Fig. 2 The difference between the parameter estimators and the true
parameters as function of number of observation for sample set (number
of experiment) of 2000.

Instead of showing the standard deviations of the estimators for the
parameters, we will rather look at the consequences of these
uncertainties in our target value, \( x_{3h} \). Consider the same simulated data as
before. For each of the simulated samples of size \( N \), the value of the 3-
hour maximum impact not exceeded by probability \( p \) reads:

\[
\hat{x}_{3h} = \hat{\mu}_j - \hat{\beta}_j \ln(-\ln(p)); j=1,2,...,M
\]

(3)

The uncertainty in the predicted extreme characteristic, \( x_{3h} \), was calculated
for \( p=0.9 \) and 0.95. Number of experiments was set to be 2000.
Fig.3 shows the 90% band of occurrences of \( x_{3h} \) versus sample size \( N \).
The close relation between number of observations, $N$, and the uncertainty of the predicted extremes is clearly seen. For sample sizes as those involved in the present study, very large uncertainties will be associated with the predicted extreme value. This will be illustrated when the model test results are compared to the prediction based on the DNV(2007).

![Graph](image)

Fig.3 Illustration of the uncertainty of the 90% range of the extreme values as function of number of observation. The 90% range have been normalized with the ‘true’ value obtained from Eq. (2) using the “true” values of $\mu$ and $\beta$.

**ELIMINATION OF FORCE PANEL DYNAMICS**

During model test, the wave impact loads were detected by force panel/transducer. The wave impacts were recorded as the responses of the panel and not as the explicit external forces. When slamming occurs, the panel of the force transducer will shrink or grow as reaction to the pressure or suction force of the slam. This reaction affects the amount of electricity passing through the transducer. Prior model test, the transducer has been calibrated and a relation between strain (corresponding to force) and voltage recorded has been established. Knowing the voltage, we will know the measured response of the force transducer. When model test is performed, acquisition data system records the slamming force based on above process in real time and then stores time-series data in digital file.

The reader must be aware of that the calibration of the force transducer has been done in dry condition. Weight applied for calibration is also of static nature. In model test, the force transducer and force panel form a mass-spring-damper system. As this system is exposed to an impact it will respond dynamically, i.e. the recorded force is more or less distorted by the dynamic response of the sensor. Therefore, we need to assess the sensor response and aim for removing the effect of sensor dynamics. And thus obtain an adequate estimate for the external force, $F(t)$.

The sensor response follows the equation of motion given below. The sensor response to a given force history can be found by solving this equation in time domain.

$$M\ddot{x} + C\dot{x} + Kx = F(t)$$  \hspace{1cm} (4)

The approach adopted here is to assume a force function, and calculate the corresponding response history, $Kx(t)$. Based on a comparison between measured response and predicted response, an updated force function is established. Several iterations are needed until we get a predicted response history, $Kx(t)$, which is more and less “identical” with the recorded impact signal. The identical of both histories is a necessity, especially for a few millisecond before the highest peak starts up to a few millisecond after the lowest peak ends (see Fig.4). By doing this, we have removed the dynamic response effect of the force transducer. The resulting external force is now taken as an estimate of the actual slamming force. In the numerical integration, $M$, $C$, and $K$ are assumed to be constant. In reality, the mass (including added mass) and damping of the system vary in time. Since the impact event usually last for very short time (20-100ms), the assumption used herein is assumed to be valid. The typical dynamic amplification for a severe slamming event is 1.25. See the Appendix.

![Graph](image)

Fig.4 Typical simulation for eliminating the force panel dynamics.

**SELECTION OF THRESHOLD**

At the initiation of this study, a threshold was introduced in order to exclude events that would not represent impacts caused by breaking waves. Only impact loads larger than threshold were considered as slamming events. For the semisubmersible case, a threshold of 50 kPa was introduced. The same level was also applied for the TLP case.

It can be questioned why a threshold level of 50 kPa was chosen. A high threshold is preferable in order to obtain a well defined population. A disadvantage of a high threshold is that the number of available observations are considerably reduced. A good choice will have to be a compromise.

In the study we considered two different approaches. One approach was a peak over threshold approach where we considered all events above the selected threshold. The other approach that we adopted was to primarily look at only the largest event during a certain time window. The length of the time window was equal to the length of the modeled test runs, i.e. 3 hours full scale duration. Here we will present the results for the latter approach and for that reason we do not discuss choice of threshold. But if the first approach is considered, this is an important subject.

**STOCHASTIC ANALYSIS ON PREDICTING EXTREME BREAKING WAVE LOADS**

As has been mentioned earlier, the main objective of this paper is to predict extreme loads due to breaking wave impact. Here, we consider the 3-hour maximum. For this approach we know the distribution function must (at least asymptotically) belong to the family of extreme value distribution. The method is described below and applied both for the semi-submersible and the TLP. Since a rather limited number of severe impacts are expected per 3 hours, one can question if the asymptotic assumption is fulfilled.

The wave impact pressures are obtained from model tests for several selected sea states, which have been chosen based on environmental contour line method, see Fig. 1. The main purpose of the model test is to collect data and identify the worst sea state in view of the response under consideration. Here, we only consider the measured force on platform columns. There are 3 force panels for the semi-submersible mounted above each other on one of the up-wave columns, see Fig. 5a.
For the TLP two force panels are installed on two different columns. Regarding location of panels on each column, see Fig. 5b.

Note: S5, S6, S7 are (3.3x3.3)m² force panel transducer.

During the initial screening, it was concluded to focus on the lowest force panel (S5) on the semi-submersible column and the panel on the up-wave column for the TLP. Regarding the semi-submersible, the force panel is mounted at 28.65m from the keel or 7.65m above still water level. The test considered are those with a wave direction normal to the column as well as the force panels. The force panel was of rectangular shape and had side dimension (full-scale) of 3.30m, i.e. an area of 10.89m². For the TLP, the panel is located 50.2m above keel or 7.65m above still water level. The force panel was of circular shape and had a diameter (full-scale) of 2.81m, i.e. the exposed panel area for the TLP is 6.2m².

It is worthwhile to notice that there is some difference between the measurements for the two platforms. The panel for the TLP is 6.2m higher than the selected panel for the semi. Thus we can expect fewer impact events for the TLP, but they may possibly in an average sense be slightly larger than impact pressures at a lower level.

The comparison between the sensor on the semi-submersible does not support that assumption. This may be a subject that could be looked further into. More important, possibly, is the difference in area between two platforms. It is reasonable to assume that the maximum impact pressure is not covering the full panel size. Thus when establishing the average impact pressure, the result obtained for the larger panel should be expected to be somewhat lower.

As said before we will herein focus on the 3-hour extreme value distribution for the worst sea state along the q-probability contour lines. When estimating a q-probability impact from the extreme value distribution, the crucial choice is the choice of percentile. For action effects corresponding to an annual exceedance probability of 10⁻², NORSOK (2007) suggest a 90 -percentile if a lower number can not be documented. For action effects corresponding to an annual exceedance probability of 10⁻¹, NORSOK (2007) gives no recommendation regarding percentile. We expect percentile level to increase with reducing target annual exceedance probability. Therefore we will here adopt the 95% - value for estimation of 10⁻¹ probability impacts.

Among the selected sea states, the analyses showed that the extreme breaking wave loads were predicted to occur for the sea states presented in Table 1.

Table 1. Extremes sea states for breaking wave loads on the column. N is the number of 3-hour realizations for each selected sea state.

<table>
<thead>
<tr>
<th>Platform</th>
<th>q=10⁻²</th>
<th>q=10⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hₜ(m)</td>
<td>Tₜ(s)</td>
</tr>
<tr>
<td>Semi-sub.</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>TLP</td>
<td>13.2</td>
<td>13.0</td>
</tr>
</tbody>
</table>

It is seen from Table 1 that the number of available observations for the 3-hour maxima is rather low for all selected sea states, keeping in mind our previous discussion of sampling variability.

Here, we want to fit the collected data into a distribution function and estimate the 3-hour extreme value. Although there is a rather limited number of major wave-impact, we here assumed that the 3-hour extreme impact will follow an asymptotic model. According to the classification of extreme value distributions, there are two types of asymptotic distribution which are dealing with the largest values when there is no upper limit, i.e.: Type I Extreme Value Distribution (Gumbel Distribution) and Type II Extreme Value Distribution (Frechet/Fisher-Tippet Distribution), see e.g. Benjamin & Cornell (1970). Our focus will be on the Gumbel model, but we will adopt the Frechet model for one of the considered cases. In view of sampling variability and small sizes, it is possible that the adoption of Frechet can be questioned. That could be assessed at some later stage. The Gumbel distribution and expressions for estimating the parameters are given in Eqs. (1 and 2).

The cumulative distribution function of Frechet distribution is given by:

\[ F_x(x) = \exp \left( -\left( \frac{x}{\lambda} \right)^k \right) \]  \hspace{1cm} (5)

where \( \lambda \) and \( k \) are the distribution parameters. Here we will estimate the Frechet parameters using a least square method.

Consider the largest events, denoted \( X \), ordered from the smallest to the largest, i.e. \( x_1 < x_2 < x_3 < \ldots < x_N \). N is number of model tests. The empirical distributions are shown in Gumbel and Frechet probability...
paper in Fig. 6 and 7. Based on the plots we will adopt the Gumbel distribution for all case except for the 10⁻² – probability case for the semi-submersible. For the latter case the Frechet model is applied. In view of uncertainties related to sample size one could possibly have used Gumbel for the 10⁻² – probability case for the semi-submersible also.

The selected probabilistic models are fitted to the data using a least square procedure. The fitted models are compared with the empirical models in Figs. 8-11. Using the fitted models, 10⁻² and 10⁻⁴ probability values are estimated using the 90- and 95-percentile values, respectively. The results are given in Table 2. Assuming the fitted parameters to be the true parameters, 90% bands for Xᵢ are indicated in the same table. It is seen from Table 2 that a very large uncertainty band is associated with the results estimated from the model tests.

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**Table 2. Extremes breaking wave impact loads (kPa).**

<table>
<thead>
<tr>
<th></th>
<th>q=10⁻²; Fₓ(ż) = 0.90</th>
<th>q=10⁻⁴; Fₓ(ż) = 0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-sub. mean</td>
<td>788</td>
<td>2637</td>
</tr>
<tr>
<td>90% band</td>
<td>483-2904</td>
<td>1741-5348</td>
</tr>
<tr>
<td>TLP mean</td>
<td>1479</td>
<td>2976</td>
</tr>
<tr>
<td>90% band</td>
<td>1011-2824</td>
<td>1854-6515</td>
</tr>
</tbody>
</table>

---

**Fig. 6** Cumulative probability of the largest slamming event, 100 and 10,000 year extreme sea states, semi-submersible.

**Fig. 7** Cumulative probability of the largest slamming event, 100 and 10,000 year extreme sea states, TLP.

**Fig. 8** Distribution fitting of the largest slamming event, sea state: Hₛ = 12 m and Tₚ = 12 s, semi submersible.

**Fig. 9** Distribution fitting of the largest slamming event, sea state: Hₛ = 13.8 m and Tₚ = 12 s, semi-submersible.

**Fig. 10** Distribution fitting of the largest slamming event, sea state: Hₛ = 13.2 m and Tₚ = 13 s, TLP.

**Fig. 11** Distribution fitting of the largest slamming event, sea state: Hₛ = 18 m and Tₚ = 16 s, TLP.
NUMERICAL PREDICTION OF q-PROBABILITY WAVE IMPACT

In the following we will adopt a procedure taken from DNV(2007). The impact force is given by:

\[ F_I = \frac{1}{2} \rho C_s A u^2 \]  

(6)

\( C_s \) is a slamming coefficient, \( \rho \) is density of sea water, \( A \) is the exposed area and \( u \) is the impact velocity normal to the exposed area. Other recommended practices (codes) adopt also this approach, e.g. API (2000). Here we will compare average impact pressures, that is we will focus on \( P_I = F_I/A \). This means that we have two quantities to assess, \( C_s \) and \( u \).

Regarding \( C_s \) we will follow the recommendation for impact against a flat plate and adopt \( C_s = 2\pi \). Regarding the particle speed, DNV(2007) recommends that \( u = 1.2c \) when loads due to wave breaking is to be calculated. The challenge with the numerical prediction is now reduced to finding the phase speed (\( c \)) of the worst q-probability breaking wave.

Following DNV(2007), the most probable largest breaking wave height in \( n \) years is estimated by 1.4 times the \( n \)-year significant wave height (1/n – probability of significant wave height), \( H_{b}^{(n)} \):

\[ u = 1.2 \cdot c_{b}^{(n)} \]  

(7)

\[ H_{b}^{(n)} = 1.4 \cdot H_{b}^{(n)} \]  

(8)

In order to indicate uncertainties related to the numerical predictions we will include two approaches that could have been interpreted as being in agreement with the recommendation.

**Approach 1:**

The significant wave height and its corresponding peak period are determined from the contour line presented in Fig.1. The breaking wave height is determined based on Eq.8. It is possible to estimate the breaking wave length, \( L_b \), by adopting the limiting steepness criterion, \( s_{crit} = H_b/L_b = 1/7 = 0.143 \). See Table 3.

Table 3. Extremes sea states and estimated breaking wave characteristics.

<table>
<thead>
<tr>
<th>Field</th>
<th>q</th>
<th>( H_b ) (m)</th>
<th>( T_b ) (s)</th>
<th>( H_s ) (m)</th>
<th>( L_s ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-sub.</td>
<td>10^{-2}</td>
<td>14.90</td>
<td>16.7</td>
<td>20.86</td>
<td>146.02</td>
</tr>
<tr>
<td>TLP</td>
<td>10^{-3}</td>
<td>18.20</td>
<td>18.7</td>
<td>25.90</td>
<td>181.30</td>
</tr>
</tbody>
</table>

The phase speed, \( c \), of a harmonic wave with wave period, \( T \), and wave length \( L \) is given by \( c = L/T \). Although the wave under consideration is far from a sinusoidal wave, we will utilize this estimate for the phase speed. For a harmonic wave in deep water we furthermore have:

\[ T = \frac{2\pi L}{c} \]  

(9)

From Eq.(9) the period of the breaking wave can be calculated. Thereafter the phase speed of breaking wave is given as \( c_b = L_b/T_b \). Using these results, the estimates for the q-probability impact loads are given in Table 4.

**Approach 2**

We will calculate the length of the breaking wave in the same way as for approach 1. However, we will not use a theoretical relation between the wave length and the wave period.

Table 4. Characteristic slamming pressures based on DNV recommendation and assume harmonic wave expressions for determining phase speed.

<table>
<thead>
<tr>
<th>Platform</th>
<th>q</th>
<th>( H_b ) (m)</th>
<th>( T_b ) (s)</th>
<th>( c_b ) (m/s)</th>
<th>( u ) (m/s)</th>
<th>( C_s )</th>
<th>( P_s ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-sub.</td>
<td>10^{-2}</td>
<td>20.86</td>
<td>11.00</td>
<td>13.27</td>
<td>15.93</td>
<td>2\pi</td>
<td>816.9</td>
</tr>
<tr>
<td>TLP</td>
<td>10^{-3}</td>
<td>25.90</td>
<td>12.29</td>
<td>14.76</td>
<td>17.71</td>
<td>2\pi</td>
<td>1009.7</td>
</tr>
</tbody>
</table>

Based on available metocean data, Mathiesen and Nygaard (2006) and Eik and Nygaard (2005), conditional 90% confidence bands for the wave period given the wave height can be prepared, see Fig. 12. It seems reasonable to assume in case wave breaking is taken place for the given wave height, selecting the lower 5% value for the wave period seems to be a reasonable empirical estimate for the breaking wave period.

**Fig.12 Relation between individual wave heights and corresponding wave periods.**

The estimated periods for the breaking waves, \( T_b \), are given in Table 5. Using these periods in combination with the breaking wave length in Table 3, the corresponding phase speed is estimated by \( L_b/T_b \). The corresponding particle speed and the resulting q-probability impact pressures are also given in Table 5. It is seen that the forces obtained by Approach 2 is somewhat lower than the results for Approach 1.

Furthermore, a floating structure will be exposed to motion due to wave and wind actions. The structure’s speed may influence the impact velocity, \( u \). Therefore, we need to take into account this effect by correcting the impact velocity prior to the slamming pressure calculation, such that \( u = 1.2 \cdot c_{b}^{(n)} \cdot \eta_1 \). Where, \( \eta_1 \) is the horizontal surge speed.

Table 5. Characteristic slamming pressures based on DNV recommendation and selecting the 0.05 quantile wave period given the breaking wave height as the breaking wave period.

<table>
<thead>
<tr>
<th>Platform</th>
<th>q</th>
<th>( H_b ) (m)</th>
<th>( T_b ) (s)</th>
<th>( c_b ) (m/s)</th>
<th>( u ) (m/s)</th>
<th>( C_s )</th>
<th>( P_s ) (kPa)</th>
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<td>2\pi</td>
<td>1009.7</td>
</tr>
</tbody>
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<tr>
<th>Platform</th>
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<th>( T_b ) (s)</th>
<th>( c_b ) (m/s)</th>
<th>( u ) (m/s)</th>
<th>( C_s )</th>
<th>( P_s ) (kPa)</th>
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</table>

**Table 5 Characteristic slamming pressures based on DNV recommendation and selecting the 0.05 quantile wave period given the breaking wave height as the breaking wave period.**
Assuming that the wave frequency surge motion is of a linear nature, the surge speed spectrum can be calculated in the frequency domain. The surge motion is characterized by the Response Amplitude Function (RAO). The RAO for the surge speed is found by multiplying the displacement RAO by $\omega^2$. Multiplying this RAO raised to second power by a proper wave spectrum for the actual sea states, the surge speed spectrum is determined. The spectral analysis is illustrated in Fig. 13. The standard deviation is found as the square root of the 0.6th spectral moment. For the semi-submersible the standard deviations are found to be 1.49m/s and 1.88m/s for $q = 10^{-2}$ and $q = 10^{-4}$, respectively.

Fig.13 Surge velocity response spectrum for semi-submersible.

For the TLP, the standard deviation of the surge speed of the platform was estimated from motion time histories from model test. By derivation of the surge motion and take the average of the standard deviation of surge velocity for all model test runs, we find the standard deviations to be 2.06 and 2.26 m/s for $q=10^{-2}$ and $10^{-4}$ respectively.

Having these values, we could re-calculate the wave impact pressure by including the platform motion effect. We only studied the effect of platform motions for the cases given in Table 5. The results are shown in Table 6. The refined approach shows that the surge motion velocity has a +/- 18-27% effect on the estimated impact pressure. It is a significant value and the effect of platform motion should be accounted for.

<table>
<thead>
<tr>
<th>Platform</th>
<th>$q$</th>
<th>$T_b$ (s)</th>
<th>$U$ (m/s)</th>
<th>$U_s$ (m/s)</th>
<th>$P_s^+$ (kPa)</th>
<th>$P_s^-$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi sub.</td>
<td>$10^{-2}$</td>
<td>11.00</td>
<td>15.93</td>
<td>17.42</td>
<td>14.44</td>
<td>977.17</td>
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<tr>
<td>TLP</td>
<td>$10^{-4}$</td>
<td>12.29</td>
<td>17.71</td>
<td>19.59</td>
<td>15.83</td>
<td>1235.78</td>
</tr>
</tbody>
</table>

**DISCUSSION: MODEL TEST VS. RECOMMENDATION**

The q-probability extremes estimated estimated from measurements together with a 90% uncertainty band around these estimates are compared with the results obtained using the DnV recommendation. The results are shown in Tables 7 and 8.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Model Test</th>
<th>90% band</th>
<th>DNV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-sub.</td>
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<td>483-2904</td>
<td>671-1056</td>
</tr>
<tr>
<td>TLP</td>
<td>1479</td>
<td>1011-2824</td>
<td>648-1080</td>
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</table>

<table>
<thead>
<tr>
<th>Platform</th>
<th>Model Test</th>
<th>90% band</th>
<th>DNV</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1741-5348</td>
<td>807-1311</td>
</tr>
<tr>
<td>TLP</td>
<td>2976</td>
<td>1854-6515</td>
<td>823-1355</td>
</tr>
</tbody>
</table>

At an annual probability level of $10^{-2}$, the DNV recommendations are more or less within the interval suggested based on model test data. But for both platforms, the DNV recommendations are in the lower part of the uncertainty band from the model tests. The observations made here and below rest of course on the assumption that our interpretation of the DNV recommended practice is in agreement with the intention of the standard.

The discrepancies between DNV recommendations and test results become more clearly pronounced for $10^{-4}$ annual probability of exceedance. For these accidental slamming pressures, the DNV recommendations fall below the 90% bands based on model test results. We may therefore conclude that if model test results are correct, then the DNV recommendations are well on the low side.

Prior to initiate an update of the DNV recommendations, it is recommended that the accidental pressures indicated herein are challenged. Is a slamming pressure (averaged over several square meters) of 2500–3000kPa reasonable? Assuming 2 participants a slamming coefficient, this would suggest a speed at impact of close to 30m/s. Is this reasonable? Maybe the slamming coefficient should be higher under certain conditions?

It is recommended that nature of these extreme impacts are carefully examined. Subjects to be considered are:

- The slamming data. Do they represent a well defined population?
- Could extremes be over estimated due to mixed population problems?
- Are Froude-scaling for these extreme impact pressures a valid approach?
- What about upper bounds for the slamming coefficient? In view of sizes of slamming panels, what could be an upper bound?

Irrespective of estimated slamming pressures, the results clearly demonstrates that the amount of test data should be increased considerably in order to reduce the uncertainty level to a reasonable level. For this sort of experiment, the number of different random seeds for a given sea states should be assessed a priori and be a part of the test planning.

**CONCLUSION**

Two approaches of predicting extreme breaking wave impact on the platform column have been described: i) a statistical analysis of model test results, i.e. stochastic analysis based on model test result, and ii) a recommendation found in a recommended practice document from DNV (Det Norske Veritas). A comparison has been carried out to two floating platform, semi-submersible platform and TLP type platform.

At a $10^{-2}$ annual probability of occurrence, the model test data yields no clear conclusion. The DNV recommendation are on the low side, but more or less included within the uncertainty band associated with the model test data.

For $10^{-4}$ annual probability of occurrence, model test results suggest much larger accidental impacts than the DNV recommendation. However, before concluding, the realism of the model test impacts should be further verified. If model test data and our treatment of the measured data are correct, the DNV recommendation are considerably underestimating the $10^{-4}$ impact pressures.
ACKNOWLEDGMENT

The model test data for both the semi-submersible and the TLP have been provided by StatoilHydro. The permission to publish this work is acknowledged.

REFERENCES


APPENDIX

Table A1. Largest Slamming (kPa) for Semi-sub.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>1.</td>
<td>116</td>
<td>106</td>
<td>1.09</td>
<td>2.</td>
<td>206</td>
<td>188</td>
<td>1.10</td>
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<tr>
<td>2.</td>
<td>129</td>
<td>122</td>
<td>1.05</td>
<td>3.</td>
<td>322</td>
<td>207</td>
<td>1.07</td>
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<tr>
<td>3.</td>
<td>149</td>
<td>119</td>
<td>1.25</td>
<td>4.</td>
<td>812</td>
<td>756</td>
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<td>4.</td>
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<td>174</td>
<td>1.04</td>
<td>5.</td>
<td>211</td>
<td>179</td>
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<td>5.</td>
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<td>156</td>
<td>1.36</td>
<td>6.</td>
<td>233</td>
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<td>1.15</td>
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<tr>
<td>6.</td>
<td>241</td>
<td>216</td>
<td>1.12</td>
<td>7.</td>
<td>307</td>
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<tr>
<td>7.</td>
<td>361</td>
<td>271</td>
<td>1.33</td>
<td>8.</td>
<td>569</td>
<td>450</td>
<td>1.26</td>
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<td>8.</td>
<td>615</td>
<td>550</td>
<td>1.17</td>
<td>9.</td>
<td>578</td>
<td>493</td>
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<tr>
<td>9.</td>
<td>745</td>
<td>716</td>
<td>1.04</td>
<td>10.</td>
<td>745</td>
<td>716</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table A2. Largest Slamming (kPa) for TLP.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
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<tr>
<td>1.</td>
<td>284</td>
<td>242</td>
<td>1.17</td>
<td>2.</td>
<td>577</td>
<td>403</td>
<td>1.43</td>
</tr>
<tr>
<td>2.</td>
<td>577</td>
<td>403</td>
<td>1.43</td>
<td>3.</td>
<td>821</td>
<td>790</td>
<td>1.04</td>
</tr>
<tr>
<td>3.</td>
<td>1050</td>
<td>871</td>
<td>1.21</td>
<td>4.</td>
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<td>871</td>
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<tr>
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<td>1113</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Note:
Rec : recorded.
Corr : corrected.
DAF : dynamic amplification factor.